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**NASA
Technical
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NASA TM-86502

**BIG MAC: A BOLOMETER ARRAY FOR MID-INFRARED
ASTRONOMY, Center Director's Discretionary Fund
Final Report**

**By C. M. Telesco, R. Decher, and C. Baugher
Space Science Laboratory**

February 1985

**(NASA-TM-86502) BIG MAC: A BOLOMETER ARRAY
FOR MID-INFRARED ASTRONOMY, CENTER
DIRECTOR'S DISCRETIONARY FUND Final Report
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16. ABSTRACT This report describes the infrared array developed in the Space Science Laboratory at Marshall Space Flight Center with Center Director's Discretionary Funds. The array, referred to as Big Mac (for Marshall Array Camera), was designed for ground-based astronomical observations in the wavelength range 5 to 35 μm . It contains 20 discrete gallium-doped germanium bolometer detectors at a temperature of 1.4K. Each bolometer is irradiated by a square field mirror constituting a single pixel of the array. The mirrors are arranged contiguously in four columns and five rows, thus defining the array configuration. Big Mac utilizes cold re-imaging optics and an up-looking dewar. The total Big Mac system also contains a telescope interface tube for mounting the dewar and a computer for data acquisition and processing. Initial astronomical observations at a major infrared observatory indicate that Big Mac performance is excellent, having achieved the design specifications and making this instrument an outstanding tool for astrophysics.					
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TECHNICAL MEMORANDUM

BIG MAC: A BOLOMETER ARRAY FOR MID-INFRARED ASTRONOMY Center Director's Discretionary Fund Final Report

1. INTRODUCTION

Sufficiently sensitive detector arrays have not been available for imaging of astronomical sources through the important atmospheric windows in the $10\text{ }\mu\text{m}$ spectral region. This report describes the infrared bolometer array developed for that purpose at Marshall Space Flight Center. Generally, images have been constructed by scanning celestial objects with the field-of-view of one detector located at the telescope focal plane. This scanning technique has several disadvantages: (1) inaccuracy of the telescope scanning causes image distortion and uncertainties in the relative position of image features; (2) temporal variations in atmospheric transmission or in the source of radiation affect the sequential observations, thereby leading to image distortion; and (3) scanning is a lengthy procedure, since the time required to generate an image is proportional to the number of desired image pixels. In addition to permitting much more efficient use of valuable observing time at large telescopes, the use of a sensitive array is often the only practical way to accomplish an observational program on fainter extended astronomical sources.

Monolithic arrays for astronomical use near $10\text{ }\mu\text{m}$ are being developed at several institutions. However, test results for these, the most promising of which are the charge injection devices (CIDs), indicate that they are, and will be for some time, 10 to 100 times less sensitive than discrete bolometer detectors when used in the high thermal background environment of ground-based observatories [1]. The lower CID sensitivity is due partly to the narrow spectral bandwidth needed to reduce the incident background radiation; the high thermal background fills the CID electron wells too rapidly for adequate charge readout to be accomplished. Even in the low background environment of space, monolithic arrays and other photon-counting devices have limited wavelength coverage; only bolometers are sensitive enough for practical use beyond $200\text{ }\mu\text{m}$.

In high background environments, bolometers are the most sensitive detectors available for use at wavelengths longer than $5\text{ }\mu\text{m}$. They can be used broadband ($\Delta\lambda/\lambda \approx 0.5-1$), are very sensitive throughout the infrared, and are both easy to use and readily available from commercial vendors. Therefore, we have developed at

Marshall Space Flight Center a unique infrared detector system containing an array of 20 discrete bolometers. Referred to as Big Mac (for Marshall Array Camera), it provides the capability of imaging relatively large fields-of-view with very high sensitivity at 5 to 35 μm .

This project, which was supported entirely with Center Director's discretionary funds, is providing MSFC with a base for more advanced infrared detector technology which will be applicable to a wide range of ground-based, airborne, and space programs. It is also anticipated that Big Mac will play an important follow-up role in the study of astronomical sources discovered by NASA's IRAS and Spacelab 2 IRT collaborative space missions, and it will provide direct support for planned space missions to study the Giacobini-Zinner and Halley Comets.

II. INSTRUMENT CONCEPT

Great care must be taken in the design of an astronomical camera that is to detect extremely faint 10 μm signals in the presence of the very high thermal background emitted by the telescope and the sky. In Big Mac, this background is minimized by: (1) cooling the bolometers and their housing to $<1.6\text{ K}$, which is also crucial for the detectors to achieve both low intrinsic thermal noise and low heat capacity; (2) housing the cold detectors and optics in an "up-looking" cryogenic dewar that directly views along the telescope optical axis, thereby eliminating additional warm beam-diverting optics; and (3) re-imaging the telescope focal plane onto the bolometer field mirrors, which substantially increases the path length between the bolometers and the external warm environment and permits much more efficient thermal baffling than possible if the field mirrors are at the principal focal plane.

The total system concept that incorporates these principles is shown schematically in Figure 1. The cryogenic dewar containing the bolometer detectors, cold reflecting optics, and spectral filters is attached to the interface box which, in turn, is attached to the Cassegrain mounting plate of the telescope. The beam of radiation exiting the telescope enters the dewar through the warm pressure window. This transparent window and the telescope primary and secondary mirrors are the only warm surfaces viewed directly by the detectors. A flip mirror in the interface box can be inserted into the beam to permit occasional visual monitoring of the field-of-view of the array. The interface box, and therefore the Big Mac dewar itself, can be easily rotated around the telescope optical axis so that any orientation of the array appropriate to the astronomical source morphology can be achieved.

NASA MARSHALL INFRARED ARRAY

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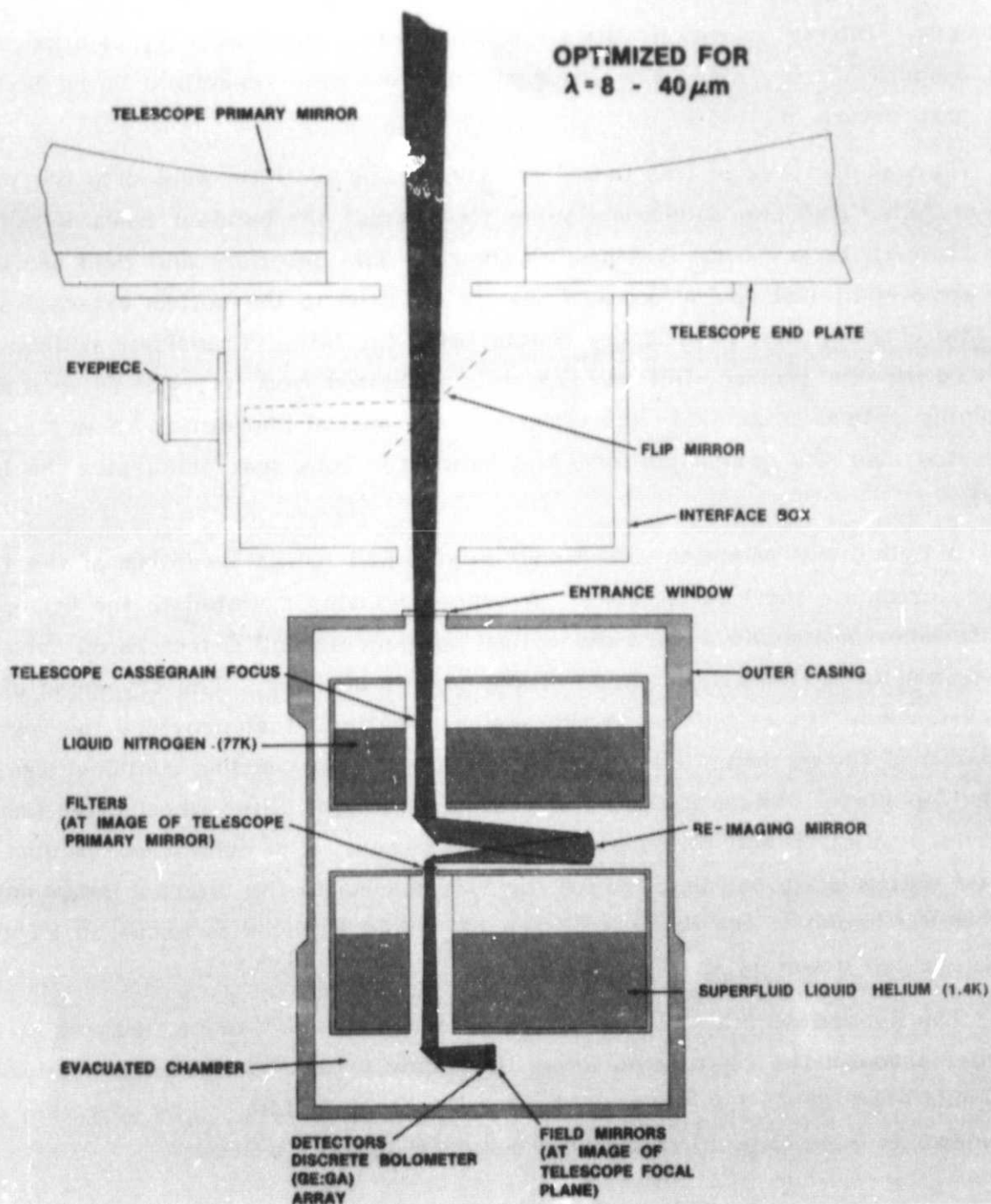


Figure 1. Instrument concept of the MSFC Infrared Array.

A. The Cryogenic Dewar

The cryogenic dewar was purchased from Infrared Laboratories, Tucson, AZ, who modified one of their standard dewars according to our specifications. This approach permitted rapid acquisition of the dewar at a relatively low cost. A cross-section of the dewar is shown in Figure 2. It contains two cylindrical cryogenic chambers. During operation, the upper chamber is filled with liquid nitrogen (LN) at a temperature of 77 K. The lower chamber contains superfluid liquid helium (LHe) at a temperature of <1.6 K.

Special features of this dewar are the optical platform welded to the top of the LHe container and two cylindrical tubes that permit the incident beam of radiation to pass through both the LN and LHe chambers. The detectors and field mirrors along with some additional optical components are mounted to the bottom external surface of the LHe chamber that is in direct contact with the LHe. Transistor modules are also mounted on this surface, but are thermally insulated from it. The filter wheel and remaining optical components are affixed to the optical platform. An exit pupil stop is located near the optical platform and inside the tube that penetrates the LHe chamber.

A cylindrical radiation shield that is attached to the lower rim of the LN container surrounds the LHe chamber. A copper housing mounted to the bottom of the LHe chamber completely covers the optical components and detectors on this surface. The transistor modules are outside of the copper housing. The cryogenic chambers are enclosed in the cylindrical dewar shell, or casing, that provides the vacuum enclosure of the system. All penetrations through the vacuum container are located on the top plate. These include the pressure window, filter wheel drive shaft, electrical connector and fill tubes for the cryogenics. The cylindrical vacuum container and its bottom plate can be removed for easy access to the internal components. A view of the inside of the dewar with the LN shield removed is shown in Figure 3, and the assembled dewar is shown in Figure 4.

The superfluid state of the LHe is achieved by continuous pumping on the LHe chamber through the fill tube to lower the vapor pressure. The fluid capacity of the cryogenic chamber is 2.5 liters of LN and 2.8 liters of LHe. The operation time after pumpdown is more than 20 hours before a refill of LHe is needed.

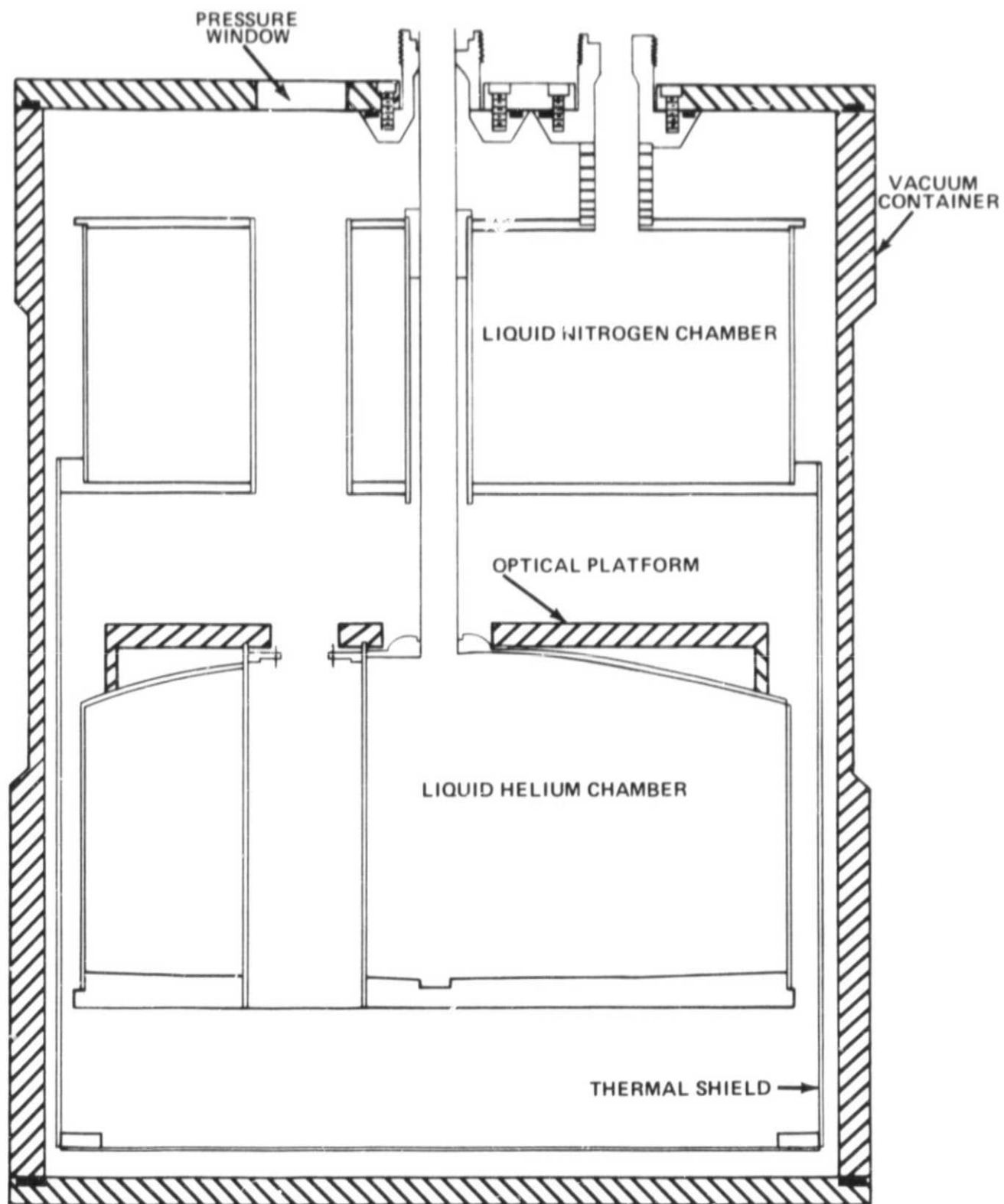


Figure 2. Cross-section view of the instrument dewar.
(Overall height 12 in.)

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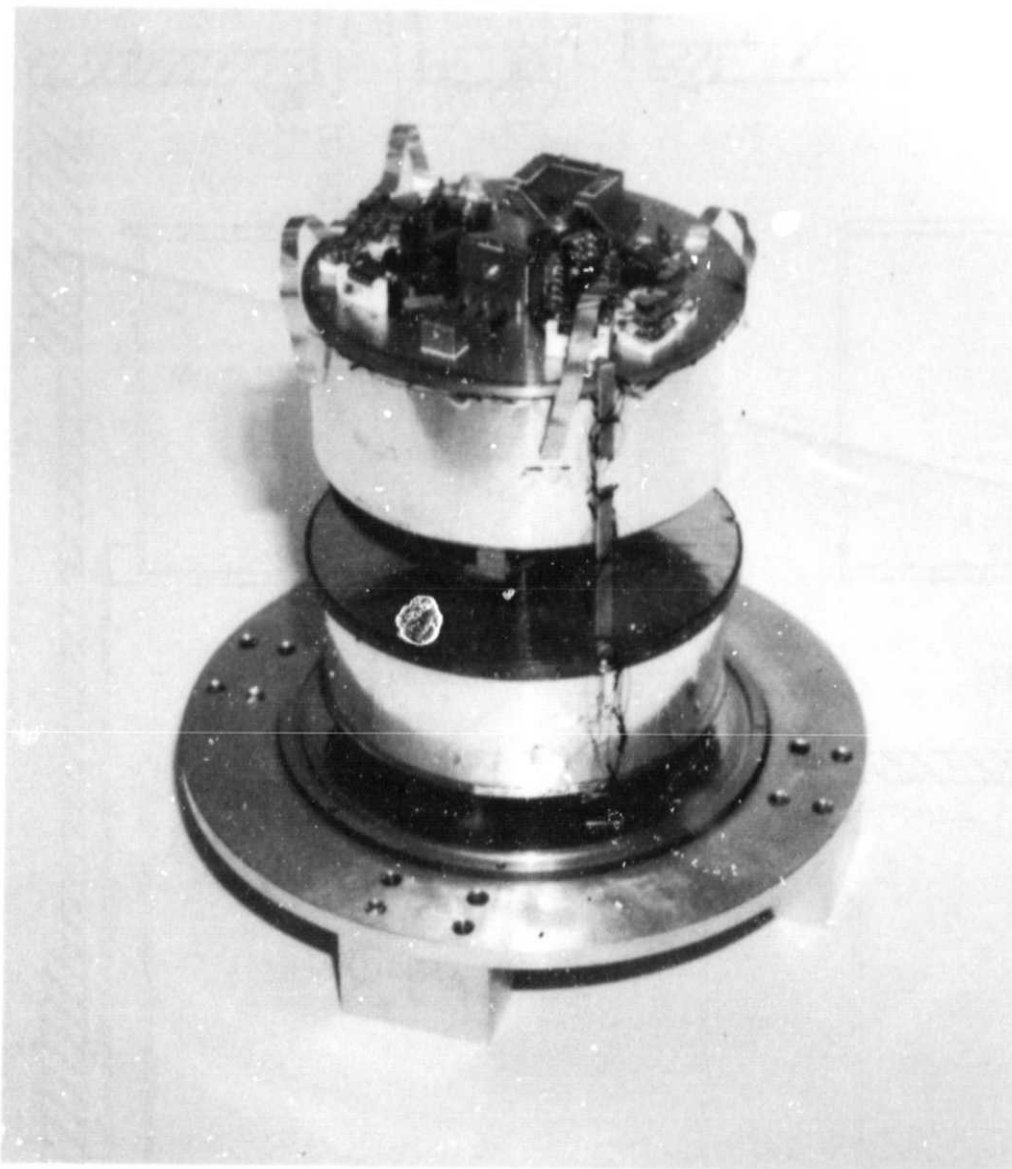


Figure 3. Inside view of the instrument dewar with thermal shield and detector housing removed.

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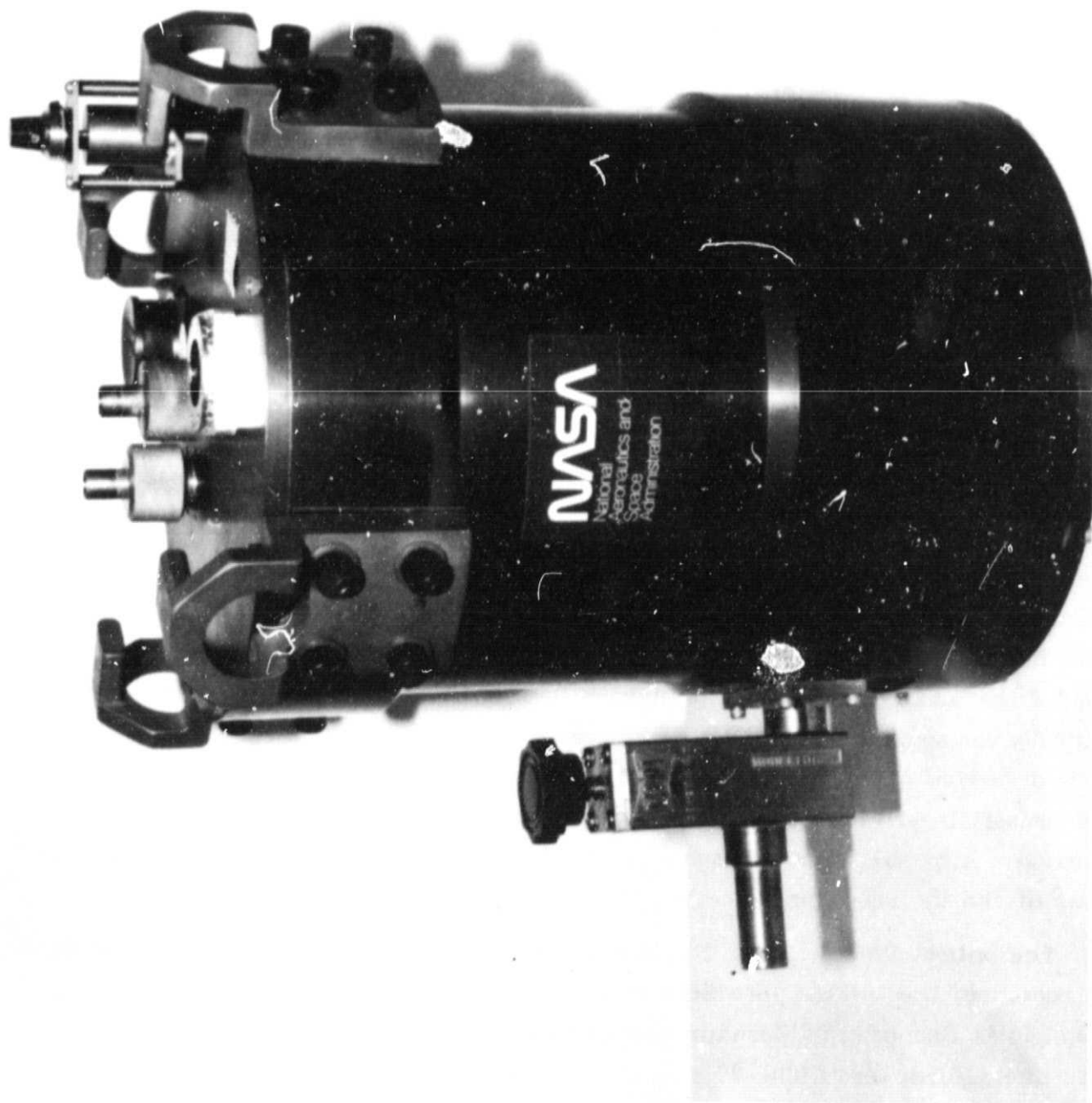


Figure 4. Assembled instrument dewar.

B. Optics and Filters

With the exception of the warm entrance window, all Big Mac optics are mounted on the outside of the LHe cryogen chamber. The inverted optical layout is shown schematically in Figure 5. All mirror surfaces are gold-coated for maximum reflectivity. Mirrors M1, M3, M4, and M5 are flat surfaces for diverting the beam by 90°. Mirror M2 is an off-axis paraboloid, and M6 consists of the 20 individual spherical field mirrors which define the array configuration and field-of-view.

After passing vertically down through the entrance window and the cylindrical hole in the LN cryogen chamber, the radiation stream is incident on flat M1 which diverts it to the off-axis paraboloid M2 (focal length = 102 mm). M2 serves two functions: to produce an image (the "exit pupil") of the telescope primary mirror at the location of the spectral filters near M3, and to re-image the telescope focal plane onto the 20 field mirrors M6. The exit pupil is only 3 to 4 mm in diameter, corresponding to the smallest diameter achieved by the ray bundle as it propagates through the system. In Figure 5, the exit pupil is located a few millimeters from M3 towards M4. Placing the filters at the exit pupil permits optimum use of continuously variable filters (CVFs) and physically small discrete filters. Most importantly, placement of a cold aperture at the position of, and nearly equal in diameter to, the exit pupil minimizes the solid angle of the ambient thermal background viewed by the detectors, thereby providing excellent thermal baffling.

After passing through the cylindrical hole in the LHe chamber, M4 diverts the radiation stream to the beam divider M5 which directs each of the two halves of the stream onto 10 field mirrors M6. The field mirrors on each side of M5 are configured in two nearly contiguous columns, each column containing five square mirrors. As viewed from "upstream," the field mirrors form a 4 x 5 array of square mirrors with practically no space between them. Since M2 re-images the telescope focal plane onto the field mirrors, they constitute the 4 x 5 array of pixels forming the image of the astronomical object of interest. Each square field mirror (focal length = 15 mm; side dimension = 4.5 mm) forms an image of the filter-wheel aperture stop (the exit pupil) on one of the 20 bolometer detectors that are the heart of Big Mac.

The optical flats M1, M3, M4, and M5 are right-angle quartz prisms that were gold coated in the MSFC Space Science Laboratory. The 28.6 mm diameter off-axis paraboloid is composed of Zerodur and was purchased from Space Optics Research Labs, Chelmsford, MA. The 20 square field mirrors are gold-coated copper and were machined and figured in the MSFC Materials Processing Laboratory.

BIG MAC OPTICS

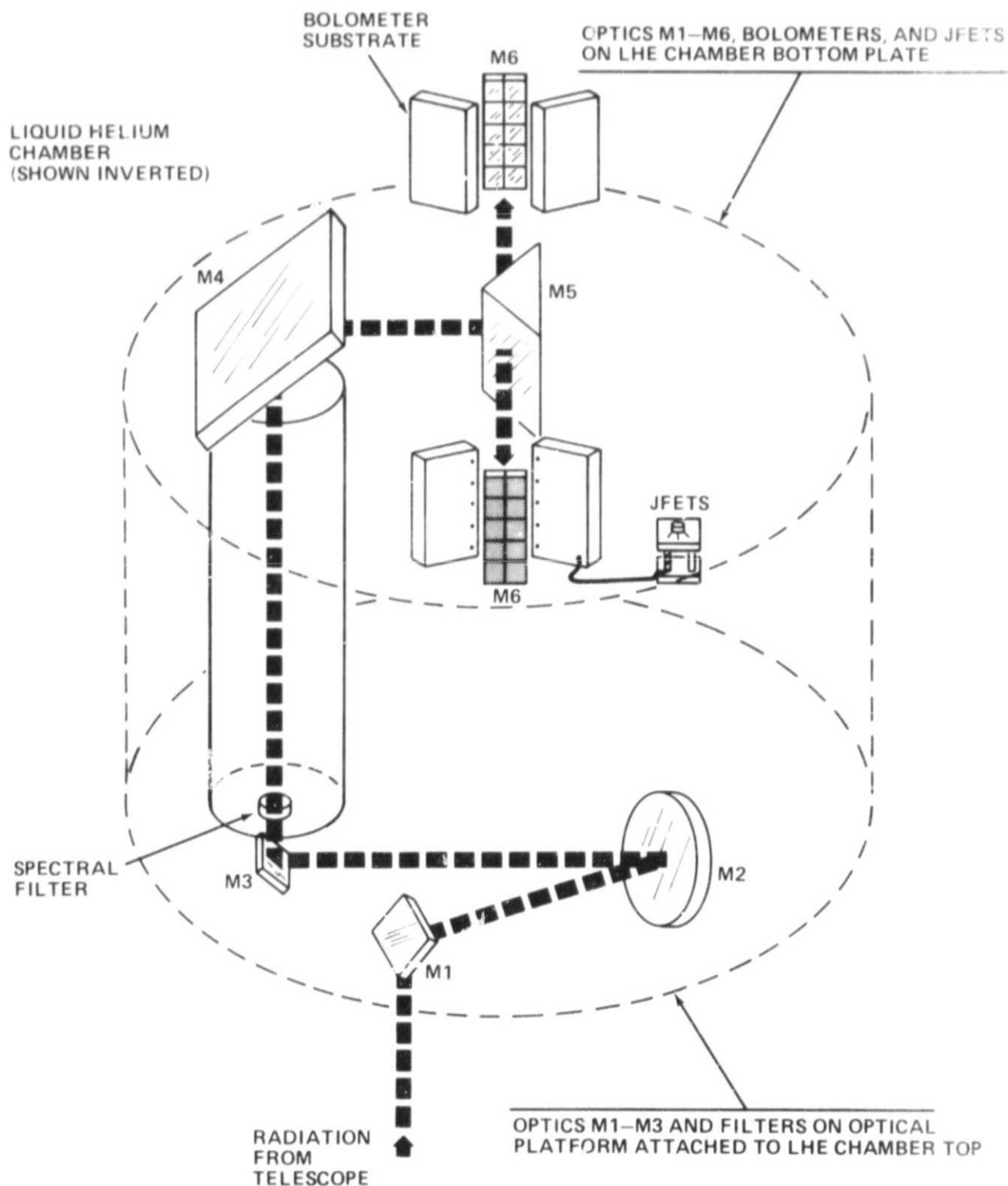


Figure 5. Ray path and optical component arrangement.

Three broadband spectral filters are currently installed on the Big Mac filter wheel: 10 μm ($\lambda_0 = 10.8 \mu\text{m}$, $\Delta\lambda = 5.3 \mu\text{m}$), 20 μm ($\lambda_0 = 19.2 \mu\text{m}$, $\Delta\lambda = 5.2 \mu\text{m}$), and 30 μm ($\lambda_0 = 29.7 \mu\text{m}$, $\Delta\lambda = 5.4 \mu\text{m}$). These are high quality interference filters produced by Optical Coating Laboratories, Santa Rosa, CA. The filter wheel is mounted to the LHe chamber on an insulating teflon block. The wheel is cold-strapped to the LN radiation shield to minimize heat input to the LHe resulting from absorption of out-of-band radiation, thus permitting lower LHe temperatures to be achieved and extending the LHe hold time. The warm entrance windows are usually composed of either KBr or KRS-5 (thallium bromide). KRS-5 is used when transmission out to 35 μm is necessary, although it has lower transmission near 10 and 20 μm than KBr. KBr, which does not transmit beyond 25 μm , is preferred when only 10 and 20 μm observations are to be made.

C. The Detectors and Cold Electronics

Each bolometer detector is a 0.3 mm diameter chip of gallium-doped germanium painted black to improve absorption efficiency. The bolometers are maintained at a temperature in the range 1.4 to 1.6 K. A bolometer operates on the principle that absorbed radiation increases the bolometer temperature, thereby altering its electrical resistance [2]. The Big Mac bolometers were purchased from Infrared Laboratories, Tucson, AZ, according to our specifications.

The circuit diagram for bolometer operation in Big Mac is shown in Figure 6. A constant bias current I_b is applied to a bolometer with resistance R_b through a load resistor R_L . For Big Mac, typically $I_b = 0.1 \mu\text{A}$, $R_b = 5 \text{ M}\Omega$, and $R_L = 10 \text{ M}\Omega$. Since the electrical resistance of the bolometer is strongly temperature dependent, a periodic change in bolometer temperature resulting from the incidence of a periodically modulated radiant signal produces a corresponding change in the bolometer output voltage. This voltage signal is applied to the gate of a nearby cold ($\sim 77 \text{ K}$) J230 junction field-effect transistor (JFET) operated in the source-follower mode. The signal voltage is read at the JFET source with essentially unity gain but with a considerable reduction in impedance. This impedance transformation close to the bolometer is essential to minimize electrical noise due to microphonics and pickup. The JFET source voltage is then fed out of the cryogenic dewar for further amplification and processing.

Although the JFETs must be located on the LHe-cooled work surface as close as possible (a few centimeters) to the bolometers, they function properly only at a much

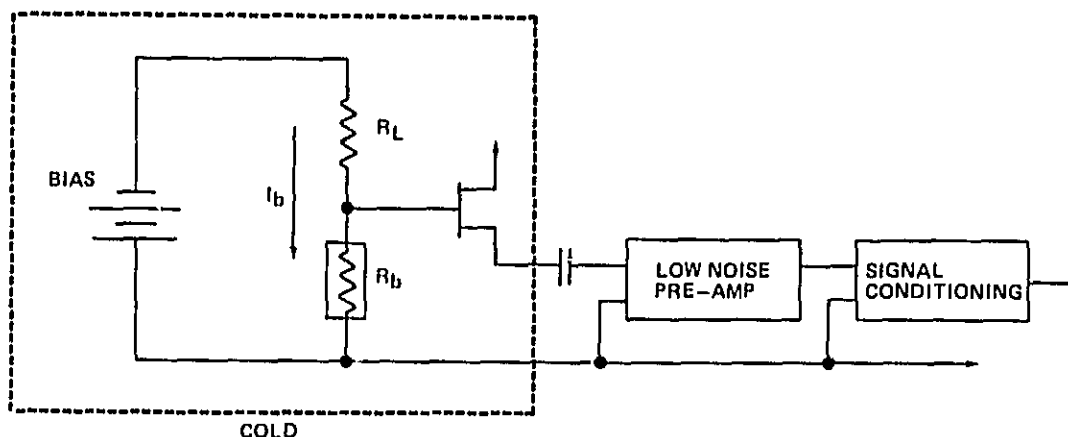


Figure 6. Bolometer circuit.

higher temperature. This is accomplished by mounting them on thermally insulating pedestals and cold strapping them to the LN-cooled radiation shield.

The bolometer chips are mounted in channels near the edges of copper blocks, or substrates. There are four substrates, each containing five bolometers. A brass shield, with one aperture for each bolometer, covers the bolometer-side of the substrate to minimize stray radiation incident on the bolometers. The miniature load resistors (Mini-Systems, Inc., type MSTF-4-S-N) are mounted on the copper substrate with the bolometers.

D. Signal Processing

The astronomical infrared signal is modulated, or "chopped," by oscillating the telescope secondary mirror with a square wave at a frequency near 10 Hz. This chopping results in the detector being alternately illuminated and dark. Phase-sensitive, or synchronous, detection techniques then permit the detection of infrared signals many orders of magnitude fainter than the "unsynchronized," or random, noise emission from the sky and other background sources.

An overview of the data system layout is presented as a block diagram in Figure 7 which also shows a summary of the signal characteristics at various points in the system. The frequency-domain spectrum is shown in the boxes at the top of the figure and the corresponding time-domain signal is shown in the circular insets. In this figure the signal is presumed to originate at the synchronous chopper where it can be considered to be a square wave with the usual square wave spectrum. At the bolometer it is converted into a voltage signal, although it is likely that some of the higher frequency components of the spectrum will have been attenuated by the

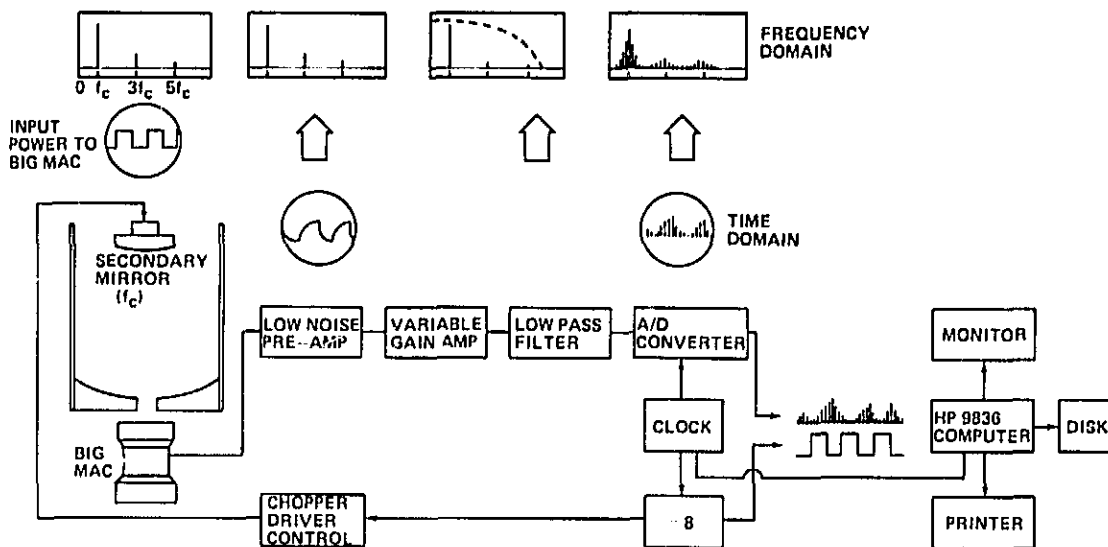


Figure 7. Signal processing block diagram.

relatively slow response of the detector element. In physical terms, the temperature of the bolometer element rises exponentially to a steady-state value when it is illuminated by the infrared signal and then cools exponentially once the radiation is cut off by the chopper.

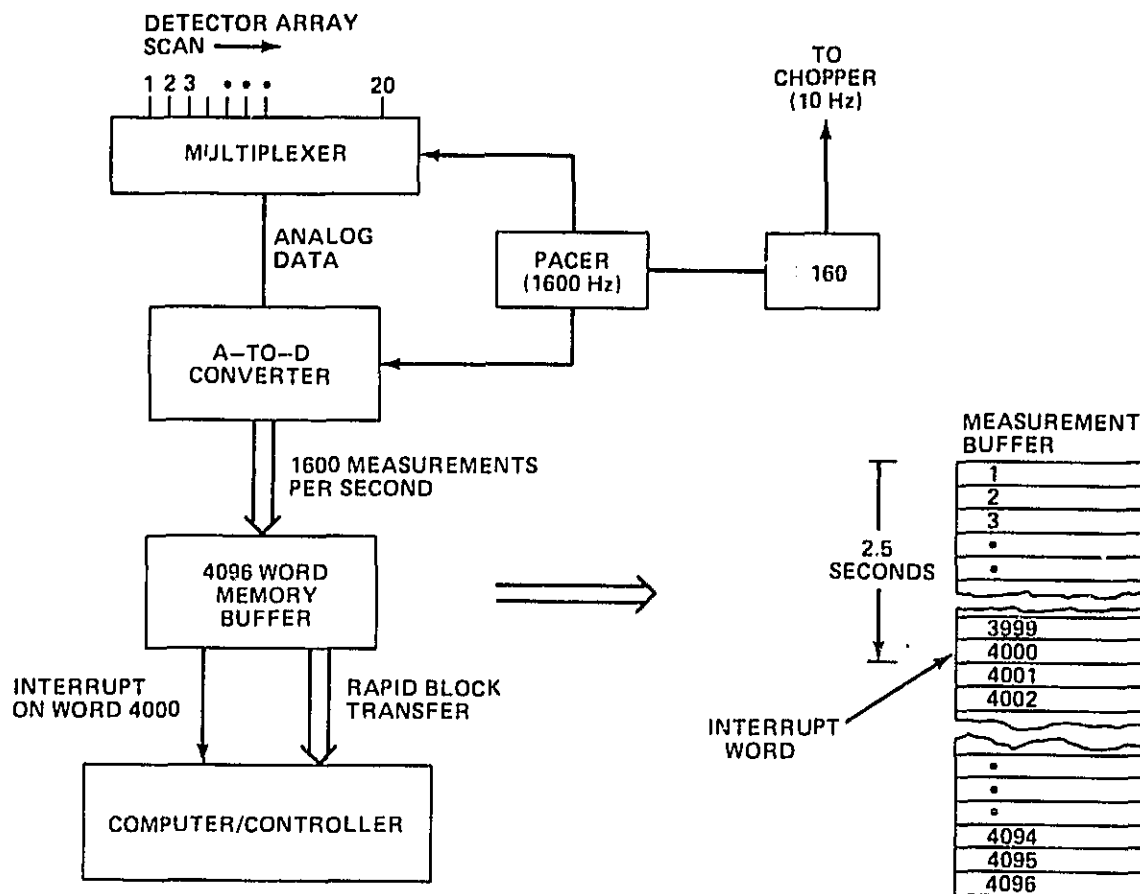
Following amplification, the signal is low-pass filtered to remove any spurious signals which might be present above the sampling frequency discussed below. Inadvertant 60-cycle pick-up would be a likely candidate although random noise processes are usually present as well. The exact selection of the cut-off frequency of the filter is not particularly critical as long as it is somewhat below the sampling frequency and does not substantially attenuate the first harmonic of the square wave signal. This approach prevents aliasing of the high-frequency noise into the signal band in the sampling process, and little is lost since signal harmonics higher than the first contain only a few percent of the total signal power.

The data sampling itself is accomplished in an analog-to-digital converter which is controlled by a clock signal. The width of each sampling interval is negligibly small compared to the modulation, or chopping, period. The sampling rate is not critical as long as it meets the Nyquist criterion for the second harmonic of the square wave; i.e., sampling should be more frequent than about six times the chopping frequency. Since it is usually easier to work in binary multiples in a digital system, a factor of eight is currently used. The synchronous loop is then completed by dividing the clock signal by eight and using the resulting square wave to drive the chopping secondary mirror of the telescope.

The final signal output is then a series of digitized voltages representing four samples taken when the bolometer is illuminated and four samples taken when the bolometer is dark. Apart from a possible phase delay caused by the finite response of the bolometer and the chopping secondary mirror, the divide-by-eight output of the clock can be used to determine which samples belong to the illuminated half cycle and which to the dark half cycle. The magnitude of the phase delay can be readily determined by cross-correlating the two signals and adjusting if necessary. At this point the data are ready for the synchronous processing. The four samples acquired on the illuminated half cycle can be averaged and differenced from the average of the four samples on the alternate half cycle and the process continued until a satisfactory signal-to-noise ratio is achieved.

When the full bolometer array is in operation the data acquisition system is receiving a substantial data flow which must be handled continuously, in a manner which allows for the computer to accomplish the described processing. To manage both of these tasks simultaneously, a system has been developed which drives the sequential scanning of the elements of the detector array and buffers a block of digitized measurements without requiring attention from the computer itself until a previously acquired block of measurements has been processed. When the computations in the synchronous averaging operation reach a convenient stopping place (and/or the measurement buffer becomes full), the computer initiates a rapid transfer of buffered measurements into memory, restarts the scanning and data buffering, and begins processing the newly received block of measurements.

A block diagram of the elements of this system is shown in Figure 8. The 20 detector elements are connected to a multiplexer which sequentially switches the analog signals to the analog-to-digital converter at a rate established by the computer controlled clock (PACER). The clock signal also synchronizes the conversion rate with the scan rate, and each time a conversion is complete the converter signals a four kilo-word buffer to store the measurement and increment its storage location counter by one. Just before the buffer fills up, it signals the computer to begin a data transfer, and the buffer memory begins emptying from the top into the computer memory. As the top of the memory buffer is emptied there is room created for more measurements so the filling process can continue in a "round-robin" fashion until the faster emptying process catches up. The interval between the beginning of the filling process and the signal from the buffer memory to start the transfer of data is the time interval available for numerical processing of the previous measurement block.



ARRAY DATA ACQUISITION AND PROCESSING
—RATES ARE FOR 10 Hz CHOPPING—

Figure 8. Data acquisition and processing concept.

The timing of these processes is fairly strict because it is necessary to maximize the time interval available for the computation processing. In the current system the block size being transferred from the 4096 measurement buffer is 5120 measurements with the interrupt to initiate the data transfer occurring at about measurement number 4000. At a chopping rate of 10 Hz, 1600 measurements per second are being taken from the 20-element array and so there are about 2.5 sec available for processing. During the remainder of the 3.2 sec required to acquire the 5120 measurement block, the system is involved in the data transfer operation. It should be noted that increasing either the number of detectors or the chopping frequency will reduce the available processing time, although there remains considerable expansion capability in the present system.

The Big Mac data system which accomplishes these tasks consists of a 16 bit Hewlett Packard 9836 computer with over 1 Mbyte of memory, as well as Winchester and floppy disk capability of more than 14 Mbytes. The D/A conversion, timing, and other circuitry are implemented with the use of an HP-6942A multiprogrammer. The system also has a printer and a wide range of color graphics capabilities.

E. Dewar-Telescope Interface

A very rigid cylindrical structure made of aluminum provides the mechanical interface between the dewar and the telescope. Figure 9 shows the dewar attached to the bottom of the interface tube which is mounted to the 2.3-meter Wyoming Infra-red Telescope (WIRO).

The upper end of the interface tube is attached to a circular plate which is supported by a stainless steel ring that permits rotation of the whole instrument about the optical axis of the telescope. The steel support ring is bolted to a flat mounting ring which permits attachment to telescopes with a variety of bolt circle patterns. The steel ring and the aluminum mounting ring are clearly visible in Figure 9.

The dewar is attached to the interface tube by four support hooks bolted to the dewar casing which engage into open slots on the tube. The unique design permits easy attachment and removal of the dewar by a lifting and rotating motion. When engaged, each of the four support hooks is clamped to the interface tube by two bolts, one from the bottom and one from the top. The optical axis of the dewar can be tipped relative to the telescope optical axis by adjustment of these bolts. The four support hooks of the dewar can be seen in Figure 4. They are electrically insulated from the metal casing of the dewar. This provides electrical insulation between the instrument and the telescope to reduce electrical noise problems.

The interface tube contains a flip mirror and a moveable eyepiece stage to check telescope pointing visually if a television monitor is not available. The interface tube wall contains several slots for the pumpline and electrical cable and for access to the filter drive mechanism. The preamplifier and variable-gain amplifier boxes are mounted on brackets attached to the outside of the interface tube.

III. SYSTEM PERFORMANCE

Extensive laboratory testing at MSFC and two engineering observational runs at a major infrared observatory permit an initial assessment to be made of the Big Mac system performance.

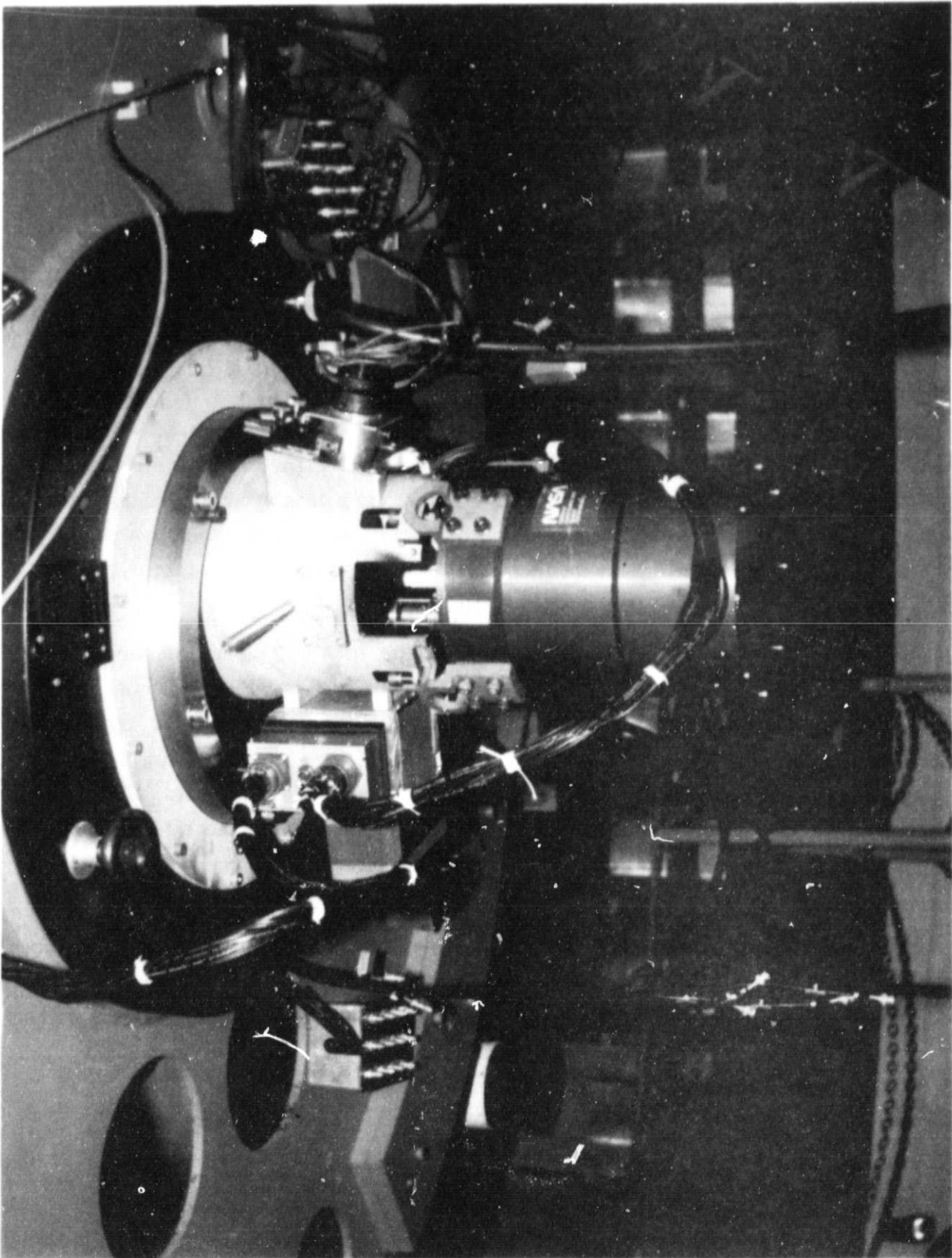


Figure 9. Big Mac attached to the Wyoming Infrared Telescope.

A. Operating Temperatures

Attaining a bolometer operating temperature below ~ 1.6 K is critical to the achievement of high detector sensitivities. Although we have not measured bolometer temperatures directly, bolometer load curves (i.e., current-voltage curves) and operating voltages can be used for this purpose. We make use of the load curves obtained by the bolometer manufacturer at a temperature of 1.3 K, and we assume that the bolometer electrical resistance varies as T^{-4} , a relation applicable in the range 1.1 to 4.2 K [3].

One detector module was tested in the Big Mac dewar under very low thermal background conditions; i.e., the detector was completely enclosed in a LHe-cooled housing with no apertures, and all other apertures throughout the cold optical path were closed. The slight deviation of our load curve from that supplied by the manufacturer implied a temperature difference of only ~ 0.03 K. This test therefore demonstrated that a sufficiently low temperature can be achieved with the Big Mac dewar if good thermal baffling is incorporated.

With the full system operational at the 2.3-meter WIRO telescope in November 1984, a temperature near 1.38 K was attained when the optical path was closed off using the blank-off, filter-wheel position. When viewing a very cold sky through our $10\text{ }\mu\text{m}$ filter, we estimate that an operational temperature of 1.41 K was achieved. Since these are not direct temperature measurements, their uncertainty is difficult to assess, but they do suggest that our system is achieving the intended operating temperature of <1.6 K. More precise laboratory temperature measurements are planned with recently acquired thermometers.

B. Optical Performance

The relatively complex optical path in Big Mac (Fig. 5) requires close attention to the alignment of each optical component. The alignment of mirrors M1 through M5 was accomplished with the use of a laser directed through the entrance window to simulate the incident radiation from a telescope. The field mirrors were aligned by viewing with a microscope the image on each bolometer of a diffuse white-light disk located at the exit pupil.

The quality of the optical alignment can be judged in two ways. First, in the laboratory a detector's angular pattern of sensitivity (referred to as the "acceptance pattern") to a distant stationary blackbody source should have a flat top and steep sides and a width (full-width at half-maximum sensitivity, FWHM) equal to the intended

telescope focal ratio; the angle of maximum sensitivity for all of the detectors should coincide. Second, at the telescope, scanning an infrared-bright star across each array pixel should imply a "beam profile" (i.e., the angular pattern of sensitivity of the telescope-dewar combination to a source at infinity) that also has a flat top and steep sides. The acceptance pattern describes how efficiently the detector system accepts radiation from the telescope secondary mirror, whereas the individual bolometer beam profiles collectively indicate the image quality of the array.

Figure 10a shows an acceptance pattern typical of Big Mac detectors. The terms "vertical" and "horizontal" refer to the orthogonal laboratory scan directions. These patterns have angular widths of approximately 2.2 deg and are considered reasonably good. The average FWHM for all 20 detectors is 2.3 deg. Since the focal ratio at WIRO is $f/26$, corresponding to a FWHM of 2.2 deg, Big Mac and the WIRO telescope seem at first sight well matched. However, the centers of the acceptance patterns for all 20 bolometers have a total spread of approximately 1 deg. Therefore, not all of the radiation incident from the secondary mirror is being accepted by the bolometers; we estimate that the loss does not exceed 20 percent and is generally much less. Since the Big Mac system design was optimized for operation at the NASA Infrared Telescope Facility (IRTF) in Hawaii, for which the focal ratio is $f/35$ (corresponding to FWHM = 1.6 deg), no significant loss of radiation should occur there.

Typical beam profiles obtained by scanning a bright standard star are shown in Figure 10b for Big Mac during the WIRO observing run in November 1984. These profiles are satisfactory, and exhibit a mean value of 7.6 arc sec (standard deviation ~ 10 percent) for the profile FWHM of all the detectors. These same tests indicate that the mean center-to-center pixel separation is 8.6 arc sec, and, therefore, at WIRO the total array size defined by the beam centers is 34×43 arc sec.

C. Sensitivity and Efficiency

The sensitivity is the most important parameter characterizing the performance of a detector system. For bolometers operating with wide spectral passbands in the $10 \mu\text{m}$ wavelength region, the noise is dominated by fluctuations in the infrared emission from the sky and warm telescope.

Our laboratory measurements indicate that the intrinsic detector noise at 10 Hz for most of the bolometers is within the range 20 to $40 \text{ nV/Hz}^{1/2}$, quoted by the manufacturer. The responsivity of the total detector system (Big Mac + Telescope + Atmosphere) determined by observing a standard star through the $10 \mu\text{m}$ filter at WIRO is $4 \times 10^5 \text{ V/W}$ for a typical array bolometer; i.e., each bolometer produces

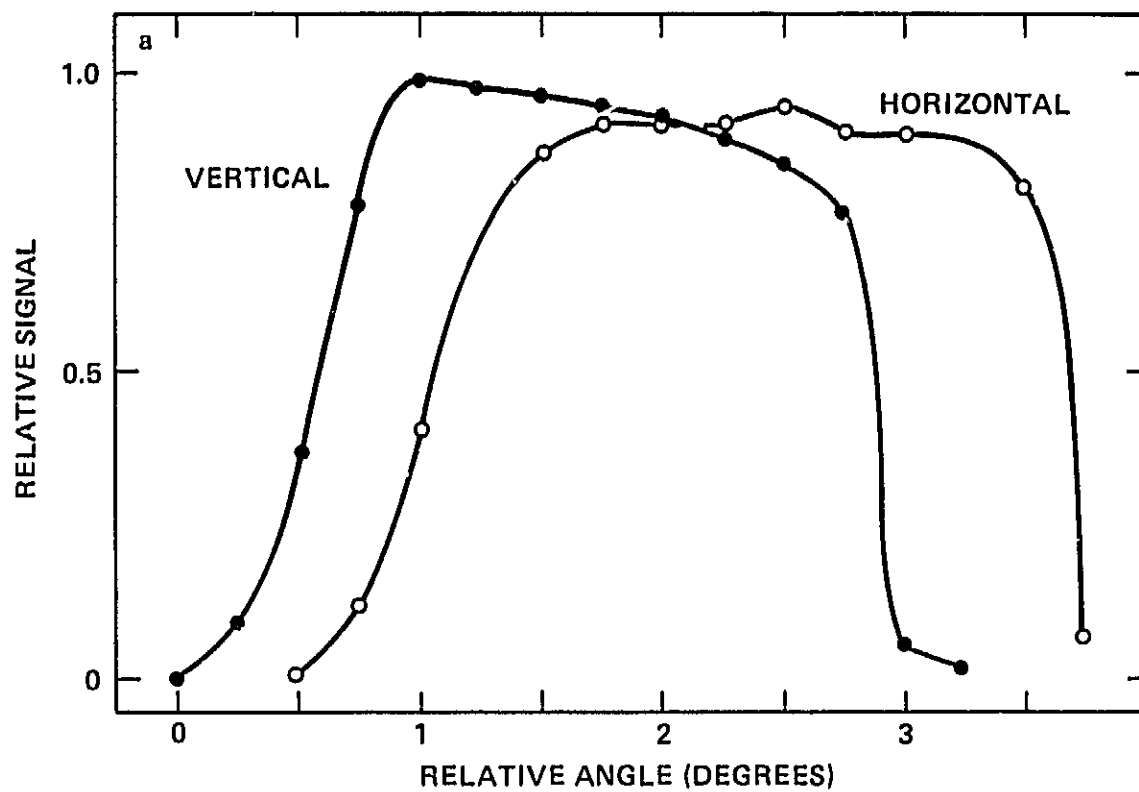


Figure 10a. Typical angular radiation acceptance pattern.

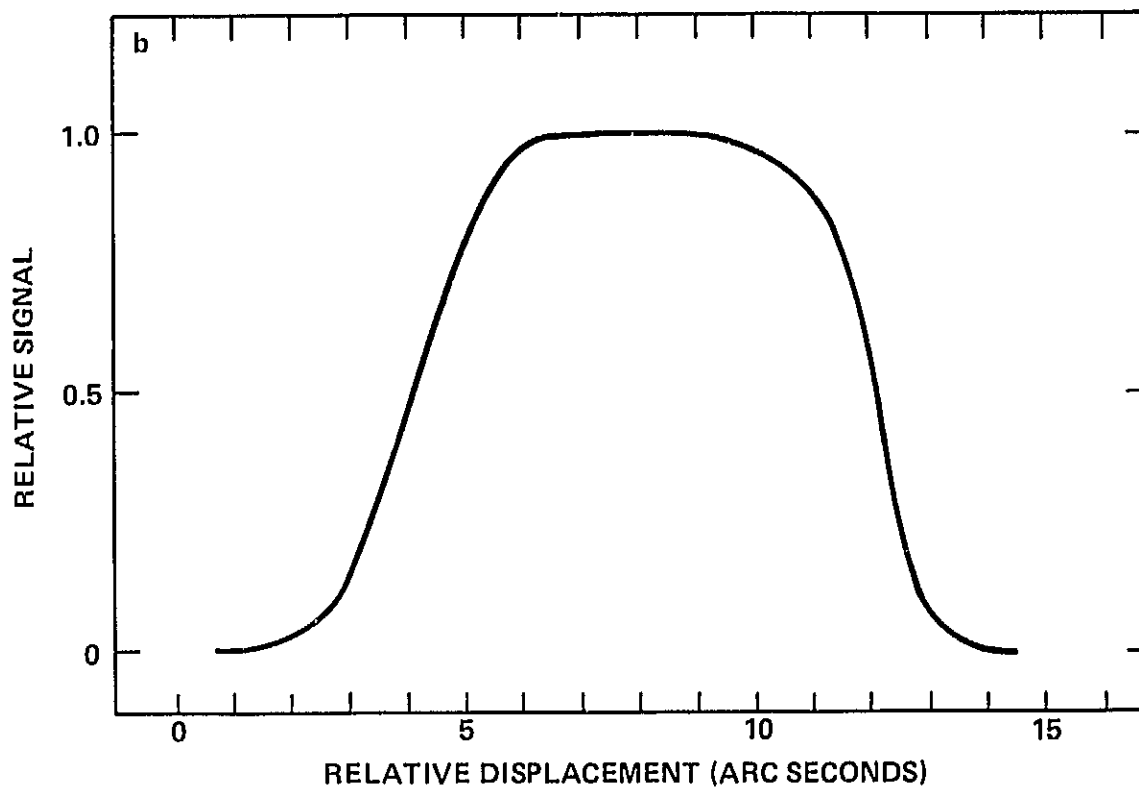


Figure 10b. Typical single detector beam profile.

4×10^5 V for each watt of power collected by the telescope primary mirror. The corresponding "intrinsic responsivity," as determined from the bolometer load curves obtained while viewing the sky through the $10 \mu\text{m}$ filter, is approximately 4×10^6 V/W. The total system efficiency is therefore ~ 10 percent. Within the uncertainties of the analysis, this value is as expected based on reasonable estimates of the transmission and reflectances of the filters, optics, and atmosphere.

The sensitivity of a detector is a measure of both noise and responsivity of the system. Using measurements of standard stars and the sky at WIRO in June and November 1984, we found that for 1 hour of integration at $10.8 \mu\text{m}$, the average value of the standard deviation of the mean was 32 mJy ($1 \text{ mJy} = 10^{29} \text{ W/m}^2 \text{ Hz}$), with the individual values ranging from 21 to 43 mJy. Adjusting these values by the factor $(D^2 F)^{-1}$ so as to apply to the NASA IRTF ($D = 3.0 \text{ m}$; $F = 35$), we expect a standard deviation of 14 mJy in 1 hour, with a range of 9 to 19 mJy. An additional factor of 0.80 adjusts to the entrance window material (KBr instead of KRS-5) used more frequently at the IRTF. Therefore, at the IRTF, Big Mac sensitivity as determined at WIRO should correspond to 11 mJy with a range of 7 to 11 mJy. The extensive experience at the IRTF of one of the authors of this report (C.M.T.) indicates that the IRTF single channel bolometers achieve values in 1 hour that are in the range 5 to 10 mJy, depending on sky conditions, telescope mirror surface quality, etc. Therefore, Big Mac sensitivity is comparable to the sensitivity of the IRTF single bolometer detectors, which are among the most sensitive in the world. We conclude that excellent Big Mac performance has been achieved.

D. Observational Results

The two observing runs at WIRO have provided important information on Big Mac performance. While most of this data is of an "engineering" nature, some astronomical maps that demonstrate the system capabilities were made. Figure 11 presents a $10 \mu\text{m}$ map of the Seyfert galaxy NGC 1068. This map, composed from data at 59 positions, was made in June 1984 using the WIRO data system (i.e., prior to delivery of the Big Mac data system) which accommodated 12 of the 20 Big Mac channels. The channels were configured in a 3×4 array (3 in RA and 4 in Dec) with dimensions 26×34 arc sec. This map was made during a few hours of morning twilight, and would have required several nights observing with a single detector. The map spans a region 42×60 arc sec and is a strictly tentative result. The $10 \mu\text{m}$ contours are shown overlaid on a visual photograph [4] of the galaxy.

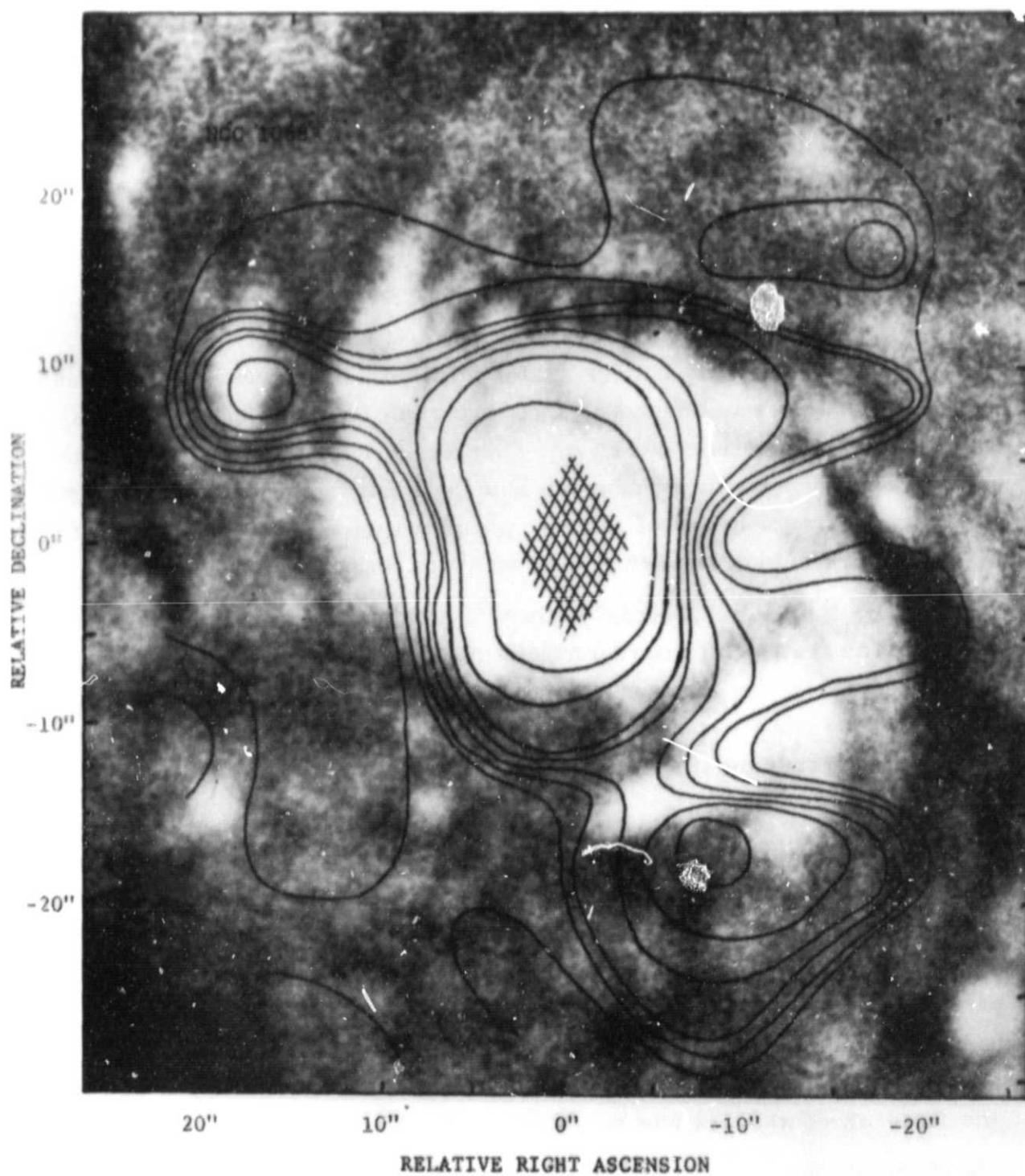


Figure 11. 10 μ m contour map of galaxy NGC 1068 obtained with the Big Mac at WIRO and overlaid on a photographic image of the galaxy.

The 10 μm observations with Big Mac at WIRO show previously observed bright infrared emission at the active nucleus and much previously unobserved emission throughout the disk. The 10 μm emission originates in warm dust. While the nature of the sources which heat the nuclear dust grains is unknown (possibly a black hole), the extended 10 μm radiation is emitted by dust heated by very young stars, many of which are completely hidden visually [5]. Only infrared observations like those made with Big Mac can fully sample the population of young stars, thereby providing insight into the important process of star formation which is intricately interwoven with the evolution of galaxies.

IV. FUTURE DIRECTIONS

Big Mac is an outstanding instrument for infrared astronomical research, and a major goal is to use this valuable tool to make important contributions to science through extensive ground-based observing. Big Mac will be applicable to a wide range of programs, such as IRAS follow-up and the study of the Halley and Giacobini-Zinner Comets. The regular use of Big Mac will necessitate some modification of the system hardware to facilitate regular maintenance and to increase efficiency.

For example, the cold electronics modules containing the JFETs must be easily repairable, permitting straightforward replacement of malfunctioning transistors. A project supported by Center Director's discretionary funds is now underway in our laboratory to develop multi-transistor modules that permit convenient component replacement while maintaining transistor integrity at the ultra-low Big Mac temperatures.

Significant upgrading of Big Mac can be accomplished through the acquisition and installation of additional bandpass spectral filters. Big Mac now contains three broadband filters near 10, 20, and 30 μm . The addition of narrowband filters spanning the 8 to 14 μm range and near 20 μm will provide uniquely important information pertaining to the physical structure of a broad range of astronomical sources including comets and galaxies. The use of a large number of filters will necessitate the implementation of a stepper motor attached to the dewar to permit remote operation of the filter wheel which is now operated manually.

It is apparent that the use of field mirrors like those in Big Mac will result in a prohibitively complex optical layout for infrared arrays with many more than 20 discrete detectors. This difficulty results from the necessity of placing the detector substrates, or supports, at locations where they do not interfere with the beam

incident on the field mirrors (refer to Fig. 5). Big Mac utilizes a beam divider (M5) to circumvent the problem, but it is evident that more detectors cannot be straightforwardly accommodated. A better solution is to use light pipes, or cones, with the bolometer placed at the exit end of the cone. Large numbers of these cones can be packed together, while permitting straightforward optical alignment. Center Director's discretionary funds have been provided to our laboratory to study the use of special light cones at mid-infrared wavelengths. An important aspect of that program will be to develop the techniques to incorporate such cones into an expanded array with significantly more than 20 detectors.

V. SUMMARY

The goal of this project was to develop a detector system consisting of an array of discrete bolometers for the purpose of making extremely sensitive astronomical observations at mid-infrared wavelengths. This goal has been achieved through the effective implementation of the up-looking cryogenic dewar concept, cold re-imaging optics and first-stage electronics, and synchronous demodulation software. The detector operating temperatures and system optical performance meet design specifications, and the sensitivity of Big Mac to faint astronomical sources is among the highest in the world. Of particular importance, the large number of detectors is significantly greater than in any other mid-infrared bolometer detector system, resulting in a substantially higher observing efficiency. The Space Science Laboratory at Marshall Space Flight Center has therefore developed an infrared detector array that will undoubtedly make important contributions to astronomy and serve as a strong basis for further technological development.

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APPROVAL

BIG MAC: A BOLOMETER ARRAY FOR MID-INFRARED ASTRONOMY, Center Director's Discretionary Fund Final Report

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The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.



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